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AUDITORY LOCALIZATION: AN ANNOTATED BIBLIOGRAPHY

Interim Report

by

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November, 1983

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20. ABSTRACT

A search was conducted using a broad range of literature sources for past research which might be pertinent to the relationships between hearing protection devices and human auditory localization. The resulting annotated bibliography is organized into several subject areas.

TABLE OF CONTENTS

INTRODUCTION

This bibliography pertains specifically to the relationships between human auditory localization ability and properties of hearing protection devices. It was assembled as an integral part of a contract between the United States Army Medical Research and Development Command and the Psychology Department of Florida State University to develop a system for assessment of localization ability as affected by hearing protectors. More general reviews regarding auditory localization and binaural hearing may be found in recent literature.[1] This bibliography excludes publications concerned primarily with physiological aspects of auditory localization. Although relevant, inclusion of that field would greatly increase the size of this report and the field is adequately covered by other reviews.[2] Auditory localization by other species is also excluded as a primary field of interest. This area is also covered by a reasonably recent review.[3]

To generate the citations in this bibliography, searches were conducted in the library facilities of The Florida State University (Tallahassee), The University of Florida (Gainesville), and the Scientific Information Center at the U.S. Army Aeromedical Research Laboratory (Ft. Rucker). In addition, the following information retrieval systems were also searched:

Biological Abstracts and Bioresearch Index

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Dissertation Abstracts

Defense Technical Information Center

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Medline

National Technical Information Service

Psychological Abstracts

Scientific and Technical Aerospace Reports

Scisearch

Smithsonian Scientific Information Exchange

The resulting citations are orgainzed into subject areas which were suggested principally by the literature. The field of sound localization has evolved mainly into two subfields: binaural localization and monaural localization. Most of the subject areas presented here contain examples from both of these subfields. A large proportion of the studies specifically concerned with hearing protector effects are clinical or industrial studies. It is notable that nearly all studies in auditory localization deal exclusively with localization of stationary sources of sound. This is probably a result of limitations in instrumentation but raises a question regarding general theories of localiztion. Limitations in instrumentation may have other covert effects on the development of theory. For example, many experiments have been carried out with multiple sound sources, often without recognition of the risk of confounding localization with discrimination of transducer characteristics. Therefore, this bibliography should be considered with these limitations in mind.

FOOTNOTES for p. 1A

[1] Durlach, N. I. and Colburn, H. S. Binaural phenomena. In: E. C. Carterette and M. P. Friedman (Eds.) Handbook of perception. Vol. IV: Hearing, New York: Academic Press, 1978.

Colburn, H. S. and Durlach, N. I. Models of binaural interaction. In: E. C. Carterette and M. P. Friedman (Eds.) Handbook of Perception. Vol. IV: Hearing, New York: Academic Press, 1978.

Moore, B. C. J. An introduction to the psychology of hearing. 2nd ed., New York: Academic Press, 1982.

[2] Altman, J. A. Neurophysiological mechanisms of sound-source localization. In: G. V. Gersuni (Ed.) Sensory processes at the neuronal and behavioral levels. New York: Academic Press, 1971.

Masterton, R. B. and Imig, T. Neural mechanisms of sound localization. Annual Review of Physiology. Palo Alto: 1984.

[3] Erulkar, S. D. Comparative apsects of spatial localization of sound. Physiological Review. 1972, 52, 237-360.

Protectors and Hearing Aids and Sound Localization

Atherley, G. R. C., & Else, D. Effect of ear-muffs on the localization of sound under reverberant conditions. Proc. Roy. Soc. Med., 1971, 64, 203-206.

In reverberant conditions subjects wearing earmuffs made more errors of localization than in non-reverberant conditions. The number of left-right errors increased but front-back errors decreased in the reverberant condition.

Atherley, G. R. C., & Noble, W. G. Effect of ear-defenders (ear muffs) on the localization of sound. Brit. J. Industr. Med., 1970, 27, 260-265.

Fifteen foundry workers made more errors of localization wearing ear muffs than without. All S's showed increase in right/left errors. When in doubt S's made rearward judgments in preference to forward judgments.

Elfner, L. F., & Carlson, C. Lateralization of pure tones as a function of binaural intensity mismatch. Psychon. Sci., 1965, 2, 27-28.

Pre-exposure of the right ear to amplified input produced decrements in ability to lateralize dichotically presented pure tones. This decrement increased with pre-exposure duration but was unaffected by signal frequency.

Elfner, L. F., & Perrott, D. R. Localization of sound following binaural intensity imbalance. Psychon. Sci., 1967, 8, 145-146.

Ten S's exposed to 63 minutes of a 700Hz, 5db interaural intensity imbalance signal demonstrated significant changes in localization function. The effect was toward a more medial localization for targets and more variability of response in the median location.

Fisher, H. G., & Freedman, S. J. Localization of sound during simulated unilateral conductive hearing loss. Acta Laryngol., 1968, 66, 213-220.

Thirteen S's judged pulsed noise location with both ears unoccluded or with one ear occluded to attenuation of 40db. Performance was highly accurate under both conditions.

Howse, W. R., & Elfner, L. F. Identification of sound source azimuth with active and passive hearing protectors. Interim report, Army Medical Research and Development Command Project Number, 171-80-0131. United States Army Aeromedical Research Laboratory Report, Sept. 1982, in press.

A stimulus identification procedure was used to investigate the effects of active and passive circumaural hearing protectors on static auditory localization. Results indicate that passive devices tended to cause an approximate 180° shift in perceived azimuth. Active devices eliminated loclization ability.

Kemp, L. The effect of directional microphones on directional hearing. Scand. Audiol., 1975, 4, 105-109.

Twenty-two S's with bilateral hearing loss were tested with 2 behind-the-ear hearing aids fitted with directional microphones or with conventional microphones. No significant differences were shown in directional hearing between the microphone conditions.

Kuhn, G. F. Hearing Aids for Spatial Perception and Localization. U.S. Dept. of Commerce, March, 1980.

Analytical and numerical estimations of the localization cues available to hearing-aided listeners are presented. Interaural time differences are pre-

dicted on the basis of (low frequency) diffraction theory for a rigid sphere and cylinder (head and torso). The interaural time difference is bi-valued when the hearing aids are placed asymetrically relative to the median plane. This bivaluedness causes localization confusion. The high frequency localization cues are the interaural level differences and the spectrum in the azimuthal and vertical median planes, respectively.

Kuyper, P. The cocktail party effect. Audiology, 1972, 11, 277-282.

The advantage of 2 ear level hearing aids in directional hearing and in the cocktail party effect is demonstrated on 25 children aged 8-16 years.

Markides, A. Localization of speech through similar and dissimilar binaural hearing aid listening modes. Brit. J. of Audiol., 1978, 12, 65-68.

Twelve adult S's with asymmetrical hearing loss using binaural hearing aids performed localization of speech tasks. Two similar type aids (body worn), two dissimilar type aids (one body worn, one ear level) and two similar hearing aids (ear level) were employed. No significant differences in localization were noted for the various conditions.

Markides, A. Effect of homolateral and contralateral routing of signals through body-worn hearing aids on the localization ability of hearing impaired people. Audiology, 1978, 17, 346-359.

Nine symetrical conductive and 13 symetrical sensory neural hearing impaired S's with microphone pick-up on same side as body aid versus microphone pick-up on contralateral side as body aid performed localization tasks.

Localization performance was significantly better when signal was led homolaterally.

Maxon, A. B., & Mazur, M. The effects of microphone spacing on auditory localization. Audiology, 1977, 16, 438-445.

Ten S's were presented noise burst stimuli transduced through body hearing aids and played through earphones. When microphones were placed wider apart (15.2-30.5 cm) localization improved over narrower placements (5.5-12.7cm).

Nabelek, A. K., Letowski, T., & Mason, D. An influence of binaural hearing aids on positioning of sound images. J. of Speech and Hearing Res., 1980, 23, 670-687.

Binaural aids were effective in hearing impaired S's in midline localization. Monaural aids were not as effective for midline localization. Some binaural aided S's showed larger errors in lateral localization than normals. Several hearing impaired S's could not localize lateral images with the binaural aid.

Noble, W. G. Earmuffs, exploratory head movements and horizontal and vertical sound localization. J. Aud. Res., 1981, 21, 1-12.

Twenty-one normal hearing S's judged the position of a loudspeaker emitting a narrow band noise centered at 1kHz in a vertical array of 10 loudspeakers in 18^{o} steps, or in a similar horizontal arc array intersecting 0^{o} azimuth and 0^{o} vertical. S's were free to move their heads or were asked to restrict head movement. In the horizontal plane S's without earmuffs performed 95% accurately but with earmuffs accuracy fell to 50% and when head movement was restricted accuracy fell to 24%. In the vertical plane S's with earmuffs, even with head movement, yielded 19% accuracy though without earmuffs accuracy rose to 72%.

Noble, W. G., & Russell, G. Theoretical and practical implications of the effects of hearing protection devices on localization ability. Acta Otolaryn., 1972, 74, 29-36.

Fifteen S's demonstrated no difference in localization ability between standard earmuffs and earmuffs modified to fit each ear independently. In a second study ear plugs effected a smaller decrement in localization than did earmuffs. Implications for pinna role in localization are discussed.

Rintlemann, W., Hartford, E., & Burchfield, S. A special case of auditory localization. Arch. Otolaryng., 1970, 91, 284-288.

Results based on 2 clinical cases suggest contralateral routing of signal (CROS) by a hearing aid has value in providing motility cues to the blind by providing clues for locating the source of sounds that are received by just one ear.

Russell, G. Effects of earmuffs and ear plugs on azimuthal changes in spectral patterns: implications for theories of sound localization. J. Aud. Res., 1976, 16, 193-207.

Earplugs produced a systematic change in energy in the region 6-10 kHz at azimuths in the region 15^{0}-90^{0}. The same region for which a consistent rearward shift in perceived localization was found. Earmuffs completely disrupted normal azimuth spectral patterns, consistent with severed impaired localization.

Russell, G. Limits to behavioral compensation for auditory localization in ear muffs listening conditions. J.A.S.A., 1977, 61, 219-220.

Twenty-six S's given total feedback on performance were not able to adapt to earmuffs. Two S's given additional 10 practice sessions were still unable to adapt. S's could however reliably distinguish between stimuli, using unorthodox localization information.

Russell, G. Localization response certainty in normal and in disrupted listening conditions: toward a new theory of localization. J. Aud. Res., 1976, 16, 143-150.

Forty-five young adults rated certainty of localization responses to a 2-sec burst of broadband noise. Certainty ratings supported an information-transformation interpretation of the findings of rearward shift in the earplug condition and a forward response shift in the ear muff condition. It is concluded that spectral invariants are central to the localization of complex sounds in the horizontal plane.

Sung, G. S., Sung, R. J., & Angelelli, M. S. Directional microphone in hearing aids. Arch. Otolaryngol., 1975, 101, 316-319.

Three brands of directional hearing aids were tested on 32 hearing aid users. Discrimination of speech was found to be best for the aid with the greatest directional effect.

Tonning, F. M. Directional audiometry. Acta Otolaryn., 1973, 75, 425-431.

Twenty S's with binaural hearing loss (28-45db HL) were tested with and without background noise and with and without hearing aids. Without background noise the binaural aid was better for localizing than a monaural aid. Also with background noise the binaural aid gave better localization ability than the monaural aid.

Tonning, F. M. Auditory localization and its clinical application. Audiology, 1975, 14, 368-380.

The ability of hearing imparied S's to localize in the horizontal plane was examined with and without hearing aids, as compared to normal hearing S's. Directional hearing was not improved by the hearing aids employed.

Role of the Pinna and Monaural Localization of Sound

Batteau, D. W. The role of the pinna in human localization. Proc. Royal Soc., 1967, 168, 158-180.

The role of the pinna in localization is to introduce by means of delay paths, a transformation of the incoming signal which is mentally inverted to provide attenuation. The inverse transform required defines the location of the sound source. Rather simple systems of delays, attenuations and signed additions may be used to construct the inverse transforms and these could be easily realized in the nervous system. Batteau theorizes that the same method of constructing inverse transformations can apply to monaural and binaural localization.

Bauer, R. W., Matuzsa, J. L., & Blackmer, R. F. Noise localization after unilateral attenuation. J.A.S.A., 1966, 40, 441-444.

Two normal hearing S's wore earplugs for periods of 6 hours to 3 days. Predictable shifts in localization occurred with broadband noise. Reorientation to correct localization with earplugs inserted required 3 days or more unless specific training was employed.

Blauert, J. Sound localization in the median plane. Acoustica, 1970, 22, 205-213.

S's were stimulated at both ears with identical narrow band signals. Sound signals were localized in the median plane. The apparent direction of the sound was a function of the frequency of the signal and did not depend upon angle of incidence. Physical measurements of the linear distortions caused by the pinna showed the pinna and the hearing system behind the pinna work in a way that sound localization of broadband signals in the median plane can be explained.

Belendiuk, K., & Butler, R. A. Spectral cues which influence monaural localization in the horizontal plane. Perception and Psychophysics, 1977, 22, 353-358.

Seven normal hearing S's participated. Earplugs were employed to produce monaural hearing. Listeners perceived narrow bands of noise as originating from restricted places in the horizontal plane which differed depending upon spectral composition.

Bothe, S. J., & Elfner, L. F. Monaural vs. binaural auditory localization for noise bursts in the median vertical plane. J. Aud. Res., 1972, 12, 291-296.

Forty normal hearing S's with one ear or both ears functional localized sounds at either 0° or 30° in the central saggital plane. Localization was better than chance both binaurally (75% P.C.) and monaurally (65% P.C.). Although sounds were spectrally matched S's reported the source at 30° elevation to be higher in pitch.

Butler, R. A. On the relative usefulness of monaural and binaural cues in locating sound in space. Psychon. Sci., 1969, 17, 245-246.

Twenty S's with normal hearing performed localization tasks in the horizontal and vertical dimensions. Performance in locating sounds in the horizontal than a binaural block on localization. In 11-13 day old animals only monaural block disturbed localization performance. Animals raised with a monaural block took a period of 21 days to localize correctly after removal of the plug.

Comalli, P. E., & Altshuler, M. W. Effect of stimulus intensity, frequency, and unilateral hearing loss on sound localization. J. of Aud. Res., 1976, 16, 275-279.

Ten normal hearing S's with one ear occluded performed median plane localization tasks for various intensities and frequencies of narrow band noise signals. Effects of frequency and intensity were found for monaural but not for binaural listening. In monaural hearing localization of high frequencies was impaired to a significantly greater degree by low intensity of the signal than in binaural hearing.

Elfner, L. F., Bothe, G. G., & Simrall, D. S. Monaural localization: effects of feedback, incentive and interstimulus interval. J. Aud. Res., 1970, 10, 11-16.

Sixty-five S's with simulated monaural deafness localized 1 sec noise bursts with no interaural intensity cue. Veridical and nonveridical feedback demonstrated the ability to manipulate subjects' response to spectral cues. Incentive was not found to be effective in the presence of feedback. Interstimulus intervals of up to 35 sec had no deleterious effect on localization ability.

Gardner, M. B. Some monaural and binaural facets of median plane localization. J.A.S.A., 1973, 55, 1489-1495.

Localization in the anterior sector of the median plane is subserved by a monaural component, the cavities of the pinna. Binaural reception also plays a significant role including confining the apparent location of the resultant image within or near the median plane.

Gardner, M. B., & Gardner, R. S. Problem of localization in the median plane: effect of pinnae cavity occlusion. J.A.S.A., 1973, 53, 400-408.

Two normal hearing S's had pinna progressively occluded. Localization on the median plane decreased in accuracy with increasing occlusion. Also it was demonstrated that localization accuracy was higher in the anterior as opposed to posterior sector of the median plane and that high-frequency signal content was more important than low.

Gatehouse, R. W. Further research in localization of sound by completely monaural subjects. J. Aud. Res., 1976, 16, 265-273.

Eight truly monaural S's could localize in the vertical and the horizontal plane above chance level. Age and duration of deafness did not diminish localization ability. Deafness type (conductive vs. sensorineural) showed no significant difference in localization ability.

Gatehouse, R. W., & Cox, W. Localization of sound by completely monaural deaf subjects. J. of Aud. Res., 1972, 12, 179-183.

Eight monaurally deaf S's demonstrated better than chance performance on a localization task in the horizontal plane. The same S's showed chance performance on a vertical localization task. The horizontal plane performance of the monaural S's was significantly poorer than the binaural controls.

Gatehouse, R. W., & Oesterreich, R. E. The roles of the pinna and the external auditory meatus in monaural sound localization. J. Aud. Res., 1972, 12, 83-90.

Eight cats with normal binaural hearing were used. They were deafened in right or left ear. Half had partial and half had complete removal of the pinna opposite the deafened ear. Monaural cats with pinna localized at least as well as binaural cats. Monaural pinnaless cats were deficient at 20^{o} angle from midline. Cats with occluded meatus performed at chance.

Harris, J. D., & Sergeant, R. L. Monaural/binaural minimum audible angles for a moving sound source. J. Speech and Hear. Res., 1971, 14, 618-629.

Three highly experienced normal listeners with both ears open or with one ear plugged, muffed and noise masked were used to localize a moving sound source. The monaural minimum audible angles were as good as the binaural for white noise and for the lowest frequency (0.8kHz) but was inferior elsewhere.

Hebrank, J., & Wright, D. Are two ears necessary for localization of sound sources on the median plane? J.A.S.A., 1974, 56, 935-938.

Twenty S's with normal hearing were run in two experiments. Experiment I results indicate it is just as difficult to monaurally or binaurally localize median vertical plane sources that are unfamiliar. Experiment II results demonstrate that S's can be easily trained to monaurally localize familiar or unfamiliar sounds in the median plane.

Hebrank, J., & Wright, D. Spectral cues used in the localization of sound sources on the median plane. J.A.S.A., 1974, 56, 1829-1834.

Twenty-eight normal hearing subjects were used. Median-plane localization of white noise is based on spectral cues generated by directional filtering of the external ear. Front medial plane shows a 1-octave notch having a lower cut-off frequency between 4-8kHz and increased energy above 13kHz. Above median plane shows a 1/4 octave peak between 7-9kHz. Behind (posterior) median plane shows a small peak between 10-12kHz with a decrease in energy above and below the peak.

Kornburger, R. A., & Elfner, L. F. The role of pitch sensation in the monaural localization of white noise. J. of Aud. Res., 1972, 12, 235-330.

Eighteen normal hearing S's with one occluded ear were used. Signal durations employed were .01, .1, and 1 sec. Signal bandwidths employed were 2-2.15kHz, 2-3.15kHz and 2-4kHz. Signals were equated for loudness at the unoccluded ear. Additional spectral information in the wider bands led to better localization. A deterioration of localization performance with shorter bursts is concluded to result from less of pitch cues.

Navarro, M. R. Adaptation to the functional loss of pinnae in sound localization ability. J. Aud. Res., 1972, 12, 59-61.

Six normal S's with ear canals extended outward 3 inches localized white noise bursts of 40 msec duration. Performance dropped to 50% correct performance as opposed to 99% correct with open ears. One hour adaptation demonstrated no improvement in performance.

Perrott, D. R., & Elfner, L. F. Monaural localization. J. Aud. Res., 1968, 8, 185-193.

Six S's were run under (1) "normal" binaural, (2) "normal" monaural and (3) monaural conditions with signals matched for loudness. Errors in localization increased across conditions. Monaural normal listening demonstrated S's ability to use loudness cues normally present. A second study demonstrated that with training monaural localization is good with both either tone or noise signals.

Roffler, S. K., & Butler, R. A. Factors that influence the localization of sound in the vertical plane. J.A.S.A., 1967, 43, 1255-1259.

Six normal S's localized sounds in the vertical median plane without head movement. The ability of S to locate accurately required the following: (1) a complex stimulus; (2) inclusion of frequencies above 7,000Hz; (3) the presence of the pinna.

Russell, G. The role of the pinna in monaural horizontal plane localization. J. Aud. Res., 1976, 16, 68-70.

Ten normal hearing S's localized white noise signals on the side of their unoccluded ear while listening under normal-binaural, monaural-with-pinna, and monaural-without-pinna conditions. Errors in localization increased across the above conditions respectively. Hence pinna information even in monaural conditions contributes to horizontal plane localization.

Searle, C. L., Braida, L. D., Cuddy, D. R., & Davis, M. F. Binaural pinna disparity: another auditory localization cue. J.A.S.A., 1975, 57, 448-454.

Physical measurements of the transfer function from a free-field source to a microphone in the S's ear canal indicate that there are two independent localization cues generated by the pinna. For sources in the vertical median plane there is a systematic change in frequency response as a function of elevation angle, and a disparity between the left-ear and right-ear responses which also changes with elevation angle. Independent psychophysical measurements indicate that these pinna cues are detectable by S's and both are used in vertical localization tasks.

Shaw, E. A. G., & Teranishi, R. Sound pressure generated in an external-ear replica and real human ears by a nearby point source. J.A.S.A., 1967, 44, 240-249.

A rubber replica with a pinna, concha and auditory meatus with dimensions comparable to those of a human ear was constructed. Limited data for six real ears with open and blocked meatus are in good agreement with replica measurements up to 7kHz. At 8kHz on-axis response of real ears passes through a sharp maximum that is either shifted to a higher frequency or is largely absent when the sound source is above the axis.

Wright, D., Hebrank, J. H., & Wilson, B. Pinna reflections as cues for localization. J.A.S.A., 1974, 56, 957-962.

Seventeen S's with normal hearing performed a monaural listening task. The time delay between direct and pinna reflected sound is the dominant feature of sound entering the ear canal. Thresholds showed delay times of 20 sec are easily recognizable when the amplitude ratio of the delayed signal to the leading signal is more than .67. JND's agree with measurements of minimum audible angle for monaural localization.

Role of Frequency in Sound Localization

Altshuler, M. W., & Comalli, P. E. Effect of stimulus intensity and frequency on median horizontal plane sound localization. J. Aud. Res., 1975, 15, 262-265.

Ten normal listeners judged the position of a sound source in the median plane at 0^{o} azimuth and in 2.5^{o} steps right or left of midline. Narrow band noise bursts at 0.5, 3 and 8kHz were used at 10-50db SL. Only the difference limen showed frequency and intensity effects, improving significantly from 4.8^{o} to 3.6^{o} from 10-50db SL. Localization of the 3kHz signal was inferior to localization for other frequencies.

Burger, J. C. Front-back discrimination of the hearing system. Acustica, 1958, 8, 249-250.

Fifteen normal hearing subjects were tested for front-back localization accuracy. Bands of noise from 150Hz to 12,000Hz were employed as stimuli. Conditions of listening were: (1) head free, both ears free, (2) head clamped, both ears free, (3) head clamped one ear covered, (4) head free both ears covered. A notable result was that accuracy was good at 300-3,000Hz. The best condition was (1) and worst condition was (3). Accuracy was best for the high band 6,400-12,800Hz but S's did remarkably well at the low frequencies.

Butler, R. A. The relative influence of pitch and timbre on the apparent location of sound in the median sagittal plane. Percept. & Psychophysics, 1973, 14, 255-258.

Twelve normal hearing listeners located sounds originating in the median sagittal plane. The stimuli were narrow bands of noise centered at 0.63, 1.6, 2.5 or 6.3kHz. Despite a sameness of pitch all S's perceived the 0.63, 1.6, and 2.5kHz sounds as originating low, medium, and high respectively regardless of actual source position. The 6.3Hz signal was accurately located by most S's. The implication is that timbre serves as the cue for location when inadequate auditory cues are present.

Butler, R. A., & Naunton, R. F. Some effects of unilateral auditory masking upon the localization of sound in space. J.A.S.A., 1962, 34, 1100-1107.

Listeners were asked to locate various pure tones and complex sound signals delivered by a concealed loudspeaker while pure-tone or complex stimuli were delivered to one ear by an earphone. The results indicate masking can have a strong and consistent effect in pulling the apparent free-field signal toward the masked ear. The data also indicate that intensity and frequency relations between signal and mask play a major role in determining the extent to which a stimulus will pull the apparent source of sound toward the masked ear.

Butler, R. A., & Planert, N. The influence of stimulus bandwidth on localization of sound in space. Percept. & Psychophysics, 1976, 19, 103-108.

Seven normal hearing S's were run binaurally or monaurally in a localization task where they were deprived of interaural time and intensity cues. The stimuli consisted of bands of noise 1-6kHz wide centered at 8kHz. Results of study showed localization, binaural and monaural, to decrease with decrease in bandwidth. Localization of sound in the median sagittal plane was more accurate with binaural than monaural listening.

Butler, R. A., Roffler, S. K., & Naunton, R. F. The role of stimulus frequency in the localization of sound in space. _J. Aud. Res._, 1967, _7_, 169-180.

Listeners were required to locate differently filtered noise bursts in the horizontal plane. Stimulus frequencies within the range of 2-4kHz appeared closer to the median plane than stimuli higher or lower in frequency. The amount of displacement was also greater for sounds originating more peripherally. Even a noise burst appeared displaced toward the center if its frequency composition was restricted to a range of 2-4kHz. The data suggest that when a tone appears displaced toward the median plane, the interaural intensity difference provided by this signal is nearly the same as that provided by the same tone when it originates near the median plane.

Cassedy, J. H., & Neff, W. D. Localization of pure tones. _J.A.S.A._, 1973, _54_, 365-372.

Eight cats were trained to spatially discriminate sources of tonal signals. Stimuli ranged from .25 to 8kHz. Discrimination thresholds changed little across frequency from .25 to 2kHz, then increased greatly at 4kHz and decreased again at 8kHz. Similarities and differences in the performance of humans and cats in localization of pure tones are discussed in relation to the possibility that the cat, like the human, uses differences in binaural time and intensity as the principle cues in sound localization.

Elfner, L. F., & DelAune, W. R. Effect of frequency and aural acuity on lateralization. _J. Aud. Res._, 1977, _17_, 1-4.

Forty normal hearing S's sensitivity to intensity-produced lateral shifts to a binaurally fused and centered auditory image was determined. Stimuli were pure tones of 0.5, 1, 2, 4, or 8kHz at 30db SL. A significant trend toward diminished sensitivity to higher frequencies was determined. No effect of interaural intensity imbalance was observed for detectability of right vs. left direction of shift.

Fedderson, W. E., Sandel, T. T., Teas, D. C., & Jeffress, L. A. Localization of high-frequency tones. J.A.S.A., 1957, 29, 988-991.

Five normal hearing S's lateralized tonal images to a binaurally produced noise image. The major conclusion is that high frequency pure tones where there is no cue provided by stimulus onset, demand a difference in level at the two ears which can be provided only by tones above 5.0kHz. At lower frequencies, where diffraction around the head is less and the difference level smaller, S considerably underestimates the azimuth angle. This underestimation decreases with increasing frequency and increases with increasing azimuth angle. The 2kHz signal showed invariably larger minimum audible angle than the .5 and 5.0kHz signals over all onset durations.

Perrott, D. R. Role of signal onset in sound localization. J.A.S.A., 1969, 45, 436-445.

A study is reported on the effects of different signal-onset conditions as a function of signal frequency on the minimum audible angle in a free field localization situation. Transient binaural differences associated with signal onset were computed on the basis of (1) Binaural distance difference, (2) head shadow effect, and (3) rise time of the signal. The results indicate that signal onset may be treated as a short duration binaural intensity-difference cue.

Perrott, D. R., & Barry, S. H. Binaural fusion. J. Aud. Res., 1969, 3, 263-269.

Seven young adults with normal hearing were used to determine the limits of binaural fusion of dichotic pure tones differing only in frequency. The mean limits increased as a direct function of the overall frequency region of the tones in a frequency dependent manner. At the low frequencies where head shadow is negligible there is a small tolerance for dichotic frequency disparity and the converse is true at the higher frequencies.

Perrott, D. R., & Musicant, A. D. Rotating tones and binaural beats. J.A.S.A., 1977, 61, 1288-1292.

Two normal hearing S's listened to rotating tones and beats as a function of the frequency of the standard and the interaural frequency ratio. Both beats and rotating tones disappeared as the frequency of the standard increased. Rotating tones were heard for large interaural frequency ratios and a single fused image was perceived. The results suggest binaural beats and rotating tones may be mutually exclusive phenomena with the latter dependent upon the binaural capacity to fuse disparate signals and the peripheral auditory system's capacity to code the temporal information present in the signal's microstructure.

Roffler, S. K., & Butler, R. A. Localization of tonal stimuli in the vertical plane. J.A.S.A., 1968, 43, 1260-1266.

Eleven normal listeners judged the location of tone bursts in the median plane. Higher pitched sounds were perceived as originating above lower pitched sounds. Blind subjects perceived the same effect. The main implication of the data is that tonal stimuli have intrinsic spatial characteristics which result in the perception of frequencies with shorter periods as being higher in space than those with longer periods.

Shaw, E. A. G. Performance of external ear as a sound collector. Paper presented at Acoust. Soc. of Amer. Meeting, Cambridge, MA, June, 1979.

A mathematical analysis of the performance of the human ear as a sound collector is given. The analysis shows the ear is a very inefficient sound collector at low frequencies but performs well at its primary resolution frequency (2.7kHz). The ear almost attains its limiting value at 9kHz and remains within 6db of its limit up to 15kHz. However, when allowance is made for the energy loss in the ear drum and middle ear it is clear that the cochlea receives no more than 10% of the power available in a diffuse field at any frequency.

Time and Intensity Cues in Sound Localization

Blauert, J. On the lag of lateralization caused by interaural time and intensity differences. Audiology, 1972, 11, 265-270.

Forty subjects with normal hearing were presented a dichotic task in which they reported an oscillation of the fused image. Interaural intensity differences were significantly smaller than those due to interaural time differences. These results seem to contradict the hypothesis that the ear converts intensity differences to time differences before perception of direction of sound.

Davis, R. J., & Stephens, S. D. G. The effect of intensity on the localization of different acoustical stimuli in the vertical plane. J. Sound and Vibration, 1974, 35, 223-229.

Twelve normal hearing S's were employed to investigate the effects of using different stimuli, various intensities, and repeated stimulus presentations on the ability to localize sounds in the vertical plane. Noise was found to be more accurately localized than a speech stimulus. Increasing the sensation level of the stimulus reduced localization errors up to a sensation level of 70db where the error appeared to reach a plateau of 3.5°. There was no apparent learning process involved in the auditory localization task.

Del'Aune, W. R., Elfner, L. F., Leftwich, M., & Perrott, D. R. Effects of interstimulus interval on the listener's ability to perceive an intensity-produced lateral shift. J.A.S.A., 1971, 49, 1897.

Five practised normal hearing S's were tested on the ability to detect a lateral shift produced by an interaural intensity difference. The results indicate that the interval between the standard and the test stimuli had little effect on the S's ability to perceive a shift in the binaurally fused auditory image at frequencies of 1.0 to 4.0kHz.

Elfner, L. F., & Perrott, D. R. Effect of prolonged exposure to a binaural intensity mismatch on the locus of a dichotically produced tonal image. J.A.S.A., 1966, 39, 716-719.

Eighteen monaural hearing S's experienced six consecutive 21 min periods of exposure to frequencies of .7, 1.0, or 3.0kHz, dichotically presented with a 50db interaural intensity imbalance. Significant differences in the locus of the auditory image were found among the test frequencies. There was a differential effect on the locus of the image of the test frequencies as a function of the frequency of the saturation tone.

Elfner, L. F., & Tomsic, R. T. A methodological study of auditory lateralization. Behavioral Res. Methods and Inst., 1968, 1, 7-10.

Four normal S's served to measure just noticeable shift of a centered image. Three manners of presentation were employed: (1) an increase in intensity at one ear (2) a decrease in intensity at one ear and (3) an increase in intensity at one ear produced concommitantly with a decrease in intensity at the opposite ear. A significant difference was demonstrated between method 2 and methods 1 and 3.

Elfner, L. F., & Tomsic, R. T. Temporal and intensive factors in the binaural lateralization of auditory transients. J.A.S.A., 1968a, 43, 746-751.

Three experienced normal hearing listeners were used to investigate the ability to detect a just noticeable shift from center of a dichotic auditory image. All combinations of a .6kHz, a 6.0kHz tone and rise times of 10, 50, and 250 msec were run. A frequency-dependent relationship was indicated only for the 10msec rise time signal. It was also noted that time differences between equal intensity portions (of the two signals) were not constant throughout the rise time of the signals.

Moushegian, G., & Jeffress, L. A. Role of interaural time and intensity differences in the lateralization of low frequency tones. J.A.S.A., 1959, 31, 1441-1445.

Three normal hearing S's adjusted the interaural time relation for a noise until it appeared to be in the same lateral position as a stimulus tone. Increasing the intensity of the stimulus to an ear caused it to transmit earlier in time. Evidence is also shown that the central nervous system too, responds to interaural intensive differences and that its response is different from that of the peripheral system, when time and intensity are opposed, time has less effect on it than when time and intensity both favor the same side.

Perrott, D. R., Elfner, L. F., & Homick, J. L. Auditory spatial orientation. Percept. and Psychophysics, 1969, 5, 189-192.

Six normal hearing S's were exposed to six consecutive days of distorted binaural time and intensity cues. The S's then localized tones of .35, 1.0, and 4.0kHz. Changes in auditory spatial orientation indicate adjustments to binaurally distorted temporal and intensive cues can occur. Reorientation does not appear to depend upon the existence of vertical auditory cues.

Sandel, T. T., Teas, D. C., Feddersen, W. E., & Jeffress, L. A. Localization of sound from single and paired sources. J.A.S.A., 1955, 27, 842-852.

Three experiments are reported. In experiment I three small speakers, one directly ahead one 40° to right and to left of midline, were sounded singly. In Experiment II the sounds were presented from pairs of speakers in phase. In Experiment III the sounds were presented in pairs out of phase. The results of the three experiments support the conclusion that the localization of tones below about 1500Hz is determined by interaural time differences. For frequencies above 1500Hz differences of intensity at the two ears must be the dominant factor.

Thurlow, W. R., & Mergener, J. R. Effect of stimulus duration on localization of direction of noise stimuli. J. Speech and Hearing Res., 1970, 13, 826-838.

Fifty normal hearing S's localized the direction of bursts of noise for both high-frequency and low-frequency bands as a function of the duration of the bursts. Durations of 0.3, 1, 2, and 5 sec were used. Subjects were free to move their heads. With increase in stimulus duration, perception of elevation was slightly improved for low-band noise. A minimum of 2 sec was required to achieve best performance (still not good) for low band noise (500-1000Hz). Perception of elevation was relatively good for high band (7500-8000Hz) even at shortest durations. Perception of front-back was considerably improved by increase of duration for both high- and low-band noise.

Tobias, J. V., & Zerlin, S. Lateralization threshold as a function of stimulus duration. J.A.S.A., 1959, 31, 1591-1594.

Experienced normal hearing S's made judgments of interaural time differences of wideband noise. Threshold varied systematically with duration of stimulation. The "duration" versus interaural time disparity function reaches asymptote at approximately .7 sec indicating the binaural system may integrate information over that period of time for the type of stimulus used.

Whitworth, R. H., & Jeffress, L. A. Time vs. intensity in the localization of tones. J.A.S.A., 1961, 33, 925-929.

S's were asked to match the lateral position of one tone the "signal" by means of another, the "pointer". The two tones were presented alternately. The E selected a combination of interaural time and intensity differences for the signal. S adjusted the interaural time difference of the "pointer" until the two occupied the same lateral position. S's with normal hearing preceived the signal in two places, one strongly affected by the difference of level at the two ears, the other almost wholly dependent upon the difference of time.

Cross Modality Effects in Localization

Bermant, R. I., & Welch, R. B. Effect of degree of separation of visual-auditory stimulus and eye position upon spatial interaction of vision and audition. Perceptual and Motor Skills, 1976, 43, 487-493.

Forty-eight normal vision and hearing S's were exposed to a visual and an auditory stimulus that differed in laterality of origin. Significant effects of visual stimulation in auditory localization were found for biases of 10°, 20° and 30° visual-auditory separation, eye position (straight ahead/visual stimulus fixation) and position of visual stimulus relative to the auditory stimulus (left/right).

Comalli, P. E., & Altshuler, M. W. Effect of body tilt on auditory localization. Perceputal & Motor Skills, 1971, 32, 723-726.

Twelve normal hearing S's performed a localization task under 0°, 30°, & 60° of body tilt. Results showed that a source sounded directly above the midline of the S's head was perceived progressively displaced in a direction opposite the body tilt.

Comalli, P. E., & Altshuler, M. W. The effect of head position on auditory localization. J. Aud. Res., 1973, 13, 37-41.

Ten normal hearing subjects were studied for localization of sound as a function of head position. A train of .3 sec pulses at 1kHz that appeared straight in front of the S's head or body when the head was rotated 45° left or right of the body was used. The apparent straight ahead of a tone was found to shift in the direction of head turn for the body reference but not for the head reference.

Fobes, J. L., & Perrott, D. R. Auditory autokinesis as a function of intermodal fields. J. Exp. Psych., 1973, 97, 13-15.

Forty normal hearing S's experienced auditory autokinesis determined with a 1.0kHz tone presented dichotically as a function of the auditory field. Maximum frequency and duration of spontaneous movement of the target tone was observed in an otherwise quiet auditory field. The addition of noise presented monaurally resulted in a significant reduction in autokinesis. A further reduction was noted when uncorrelated white noise was added to both ears. The results suggest that autokinesis is dependent upon intermodal effects.

Krauskopf, J. Figural after-effects in auditory space. Amer. J. Psych., 1954, 67, 278-287.

Satiation in the median plane reduced the variability of subsequent localization determinations in the median plane. Satiation at a point removed from the median plane produced a shift in localization from the median plane in the direction of the satiating tone. The distance paradox, that is, the error should grow with greater distance from the medial plane and then decrease with a further distance increase of the satiating tone was only paritally confirmed. The distortions induced showed decay with time.

Lackner, J. R. Visual rearrangement affects auditory localization. Neuropsychologia, 1973a, 11, 29-32.

Twelve normal hearing S's had their visual field distorted by prism spectacles. The midline localization of dichotically presented clicks was directly influenced by the visual rearrangement caused by the prisms. Evidence is shown that for certain exposure conditions the visual adaptation process can be inferred from auditory perception without recourse to pointing movements of the hand.

Lackner, J. R. The role of posture in sound localization. Quart. J. Exp. Psychol., 1973b, 26, 235-251.

Twenty-four normal hearing S's were tested in an auditory localization task. The location of the perceived sound depended on both the S's perceived head position and the auditory cues at his ears. If an error wasinduced between his true and registered head posture, errors in auditory localization corresponding in time course and size resulted. The presence of visual information prevented postural errors and the resultant auditory localization errors.

Paulsen, J., & Ewersten, H. W. Audio-visual reflex. Acta Otolaryngol., 224, 211-217.

Audio-visual reflex was registered using a DC electronystagmograph on 10 normal hearing S's. The acoustic stimulus was an octave filtered band of noise centered at 1.0kHz. Deflections of the eye in the dark towards the sounds were compared to calibration curves where light signals replaced the loudspeakers. Reliability of the eye deflection was higher than the lateralization to the sound. A binaural ear-level hearing aid gave no increase in efficiency of localization over unaided ears. A pocket aid connected to the ears with a Y cord gave no lateralization at all.

Pick, H. L., Warren, D. H., & Hay, J. C. Sensory conflict in judgments of spatial direction. <u>Percept. & Psychophysics</u>, 1969, <u>6</u>, 203-205.

An artificial discrepancy was created between information about azimuth coming from different sense modalities. The resolution of this discrepancy was examined for cases of vision and proprioception, proprioception and audition, and audition and vision. Vision biased both proprioception and auditory judgments. Proprioception biased auditory judgments and had a small effect on visual judgments.

Platt, B. P., & Warren, D. H. Auditory localization: the importance of eye movements and a textured visual environment. <u>Percept. & Psychophysics</u>, 1972, <u>12</u>, 245-248.

Two experiments with 20 and 18 normal hearing S's were run. In both experiments S's pointed to auditory targets in a variety of visual conditions. The results of Experiment I showed that target-directed eye movements were important. In Experiment II eye localization was assessed along with pointing localization. Both eye and hand localization of the hidden auditory targets were better when target-directed eye movements were made in a lighted environment than when made in the dark. Data also suggested that S's have better knowledge of their eye position in the light.

Radeau, M., & Bertelson, P. The effect of a textured visual field on modality dominance in a ventriloquism situation. <u>Percept. & Psychophysics</u>, 1976, <u>20</u>, 227-235.

"Auditory capture" occured with a visual input reduced to a single luminous point in complete darkness, but not with a textured background. On the other

hand "visual capture" of auditory localization was observed both in the dark and with textured background.

Ryan, T. A., & Schehr, F. The influence of eye movement and position and auditory localizaton. _Amer. J. Psychol._, 1941, _54_, 243-252.

A careful study of effect of eye movement on auditory localization reports no consistent directional change in localization correlated to eye movement. The author reports the mere opening and closing of the eye affects the locus of the auditory image. The two S's who showed consistent shifts with eye motion reported shifts in the auditory image in opposite directions.

Thurlow, W. R., & Kerr, T. P. Effect of a moving visual environment on localization of sound. _Amer. J. Psych._, 1970, _83_, 112-118.

A number of experiments are reported concerned with rotation of a striped visual environment about a subject. The rotation caused a displacement of "straight ahead" in the direction of the rotation; also the source of a sound was perceived to displace in the direction of the rotation. The mean change in "straight ahead" was less than the change in shift in location of the sound.

Thurlow, W. R., Mangels, J. W., & Runge, P. S. Head movements during sound localization. _J.A.S.A._, 1967, _42_, 489-493.

Photographic data are reported on head movements during a localization task. High and low pass noises were used as the stimuli with a duration of 5 sec. Rotation movements of the head about the vertical axis were common alone and in combination with tipping and pivoting movements. A number of S's showed reversals in movement. In most cases the reversals were of rotation movements.

Thurlow, W. R., & Runge, P. S. Effect of induced head movements on localization of direction of sounds, J.A.S.A., 1967, 42, 480-488.

A series of three experiments are reported in which high and low frequency noise and pulse stimuli were employed in a localization task. Ten S's with normal hearing were blindfolded to remove visual cues. Sources were located to the right and left of S, in front and behind S, and above and below the plane through the S's ears. Induced head rotation was found especially effective in reducing horizontal error. Rotation, pivot, and rotation-pivot movements caused a small but significant reduction in vertical localization error for low-frequency noise stimuli.

Thurlow, W. R., & Weerts, T. C. The effect of eye position and expectation on sound localization. Percept. & Psychophysics, 1971, 9, 35-39,

Subjects who were exposed to a sound coming from straight ahead but who turned their eyes 20^{o} to the side toward a visible speaker during an exposure period and expected to hear the sound come from the 20^{o} lateral source than no significant shift. Their is some evidence of adaptation to the exposure over time.

Tolkmitt, F. J. Speed of sound localization. Australian J. Psych., 1972, 24, 103-106.

Twelve normal hearing S's localized sounds from speakers spaced equidistantly around S's head. Results support the notion that processing time is shortest for binaural cues from speakers in the aural axis. At the same time it was noticed because of the confounding motor component that latency data are

probably too insensitive to reflect systematic variations in central processing times.

Wallach, H. The role of head movements and vestibular cues in sound localization. J. of Exp. Psychol., 1940, 27, 339-368.

Experiments of synthetic production of sound directions are reported which show that either vestibular cues or visual cues can replace head movements as such. A blindfolded subject localized the sound while he was passively turned on a revolving chair, another subject observed the direction of sound while seated inside a revolving screen. Results indicate: (1) fairly accurate representation of the actual displacement of the head is furnished by visual stimulation; (2) visual stimulation, equivalent to that which actual displacement of the head would give, suffices to determine the direction of sound.

Minimum Audible Angle of Localization

Mills, A. W. On the minimum audible angle. J.A.S.A., 1958, 30, 237-246.

Difference threshold for azimuth of a source of pure tones between .25kHz-10.0kHz were determined for three normal hearing S's. The smallest angular separation detected between two successive tonal pulses (minimum audible angle, MAA) was determined. These threshold angles were analyzed in terms of the corresponding threshold changes in phase, time, and intensity of the tone at the ears of the S. A comparison of these thresholds with those for dichotic stimulation indicates that the resolution of the direction of a source is determined, at frequencies below about 1.4kHz, by interaural differences in phase or time, and at higher frequencies by differences in intensity. When conditions are optimal for temporal discrimination, the threshold for an interaural difference in time is about 10 sec and when the conditions are optimal for intensity discrimination, the threshold for an interaural difference in intensity is about 0.5db.

Perrott, D. R. Binaural resolution of the size of an array: some experiments with stereophonic arrays. Submitted for publication in J.A.S.A., 1984a.

For pure tone stimuli, optimal resolution of a stereophonic horizontal array appears within a narrow range of intersource frequency differences, at approximately 30Hz. Moreover, such extensive judgments are reliably performed only for tonal stimuli below 1500Hz. Additional tests were conducted with amplitude modulated tonal stimuli, low and hi frequency uncorrelated noise, correlated low frequency noise, and with the uncorrelated noise in both the vertical plane and under monaural listening conditions. The results of all of these manipulations support the notion that the angular extent of a multicomponent source array can be resolved if disparate low frequency energy is available from the various sources in a horizontal configuration. Discrimination of the size of an acoustic array appears to be one of the functions which can be performed by the binaural system.

Perrott, D. R. Concurrent minimum audible angle: a re-examination of the concept of auditory spatial acuity. Submitted for publication in J.A.S.A., 1984b.

Localization of concurrent events was found to be a direct function of the spectral differences between the events, the angle between the sources and the location of the sources within the field defined by the S. In the latter case the minimum audible angle was smallest with sources placed symmetrically about the S's median plane and maximal at the extreme lateral positions. Post hoc tests indicate that the spectral limits for concurrent localization is dependent both upon the angular separation of the sources and the position within the field as defined by the locus of the subject. The functions obtained approach those of Mills (1958) as the temporal overlap between the concurrent events decreased. The present results suggest that a single localization function may exist with optimal performance observed with fully successive stimuli and poorest in the condition involving simultaneous events.

Perrott, D. R., Buck, V., Waugh, W., & Strybel, T. Z. Dynamic auditory localization: systematic replications of the auditory velocity function. J. Aud. Res., in press.

Perceived velocity appears to be directly proportional to the actual speed of the source. The same velocity power function (exponent of 1) has been obtained with a variety of stimuli, subject populations, and with both direct and indirect psychophysical methods. The results of the study suggest that systematic velocity judgments can be obtained with very brief stimuli so long as the MAMA is exceeded. The capacity to judge the velocity of a moving sound source appears to be a well defined feature of the dynamic binaural spatial system.

Perrott, D. R., & Musicant, A. D. Minimum auditory movement angle: binaural localization of moving sound sources. J.A.S.A., 1977, 62, 1463-1466.

In Experiment I S's with normal hearing discriminated sound as moving or stationary. The minimum audible movement angle (MAMA) increased from 8.3° at a velocity of 90°/sec to a high of 21.2° at the fastest velocity, 360°/sec. In Experiment II four S's were asked to localize the moving source at signal onset and offset. The results indicate that the apparent onset is displaced in the direction of motion and the amount of this displacement is directly related to source velocity. Less consistent results were observed with signal offset. The results suggest that the binaural system is relatively insensitive to motion.

Waugh, W., Strybel, T. Z., & Perrott, D. R. Perception of moving sound: velocity discrimination. J. Aud. Res., in press.

A comparison of visual versus auditory velocity estimates show both modalities to be power functions of source velocity with a slope of 1.

A second study determined that the similarities between the visual and auditory velocity functions could not be attributed to either previous visual experience or proprioceptive feedback. No significant difference was found in estimating velocity of a moving source either while tracking with the eyes or while fixating on a small light. The estimates were again shown to be a power function of source velocity. The evidence is suggestive of a single velocity detecting mechanism.

Williams, K. N. Discrimination in auditory space: static and dynamic function. Unpublished dissertation, Florida State Univerity, 1978.

This study challenges recognition as an appropriate method for studying auditory spatial responses. Three experiemnts were performed. First, physical measurements were taken over the first quadrant (0^{o} to 90^{o} azimuth) and at 0^{o} and 30^{o} elevation with and without an observer present. Behavioral estimates of auditory sensitivity were taken within the physically defined field. Second, comparative recognition and discrimination auditory acuity functions were obtained by employing a two response matching task. Finally discrimination estimates of observer sensitivity to slowly moving sources were obtained. Physical measures indicate characteristic and highly individual frequency response curves at each ear over the range of spatial loci. Behavioral response was better at high frequencies when the source was located at 90^{o} azimuth than at 0^{o} azimuth. Static Minimum Audible Angle estimates (MAA) across azimuth conform to those found by others. Minimum Discriminable Angle estimates (MDA) are similar to MAA at 45^{o} azimuth. MDA's are superior to MAA's at 90^{o} azimuth. Static vertical MDA at 0^{o} azimuth also correspond to those presented in localization literature. Vertical acuity estimates obtained off the midsaggital plane represent new localization data points as do lateral estimates at 30^{o} elevation.

Lateral MDA estimates taken at 0^{o} elevation range from 2^{o} at 0^{o} azimuth to 12^{o} at 90^{o} azimuth. Estimates obtained at 30^{o} elevation are about 30% higher. MDA's obtained in the vertical dimension range between 4 and 8^{o} at 0^{o} elevation across azimuth. Vertical auditory acuity (MDA) at 30^{o} elevation is 30% to 50% worse than at 0^{o} elevation. Discrimination of acoustic source motion was superior to spatial discrimination between well defined stationary sources. Auditory Minimum Velocity Thresholds (MVT) ranged from 0.3^{o} in lateral conditions at 0^{o} azimuth to 8^{o} for lateral movement discrimination at 90^{o} azimuth. MVT functions obtained for sources moving at rates from 1^{o}/sec to 6^{o}/sec were consistently 50% better than MDA estimates taken at the same azimuth angle.

The results generated in these studies suggest that auditory acuity depends only on near field (about the head and shoulders) transformations produced by interaction of the source at a given locus with the observer. Directional estimates are possible as long as binaural time and intensity differences are appreciable whereas spectral changes provide only same or different information. High frequency sensitivity enhances spectral sensitivity to spatial displacement and motion. Implications are presented in a two stage model of localization.

Speech Localization

Fletcher, H. The nature of speech and its interpretation. Bell System J., 1921, 1, 129-144.

The intensity of undistorted speech received by the ear can be varied from 100 times greater to 1,000,000 less than the initial speech intensity without noticeably affecting its intelligibility. Any apparatus designed to reproduce speech and preserve its characteristic qualities must transmit frequencies from 100Hz to 5,000Hz with approximately the same efficiency. Although most energy in speech is carried by frequencies below 1,000Hz, the essential characterisitcs which determine its interpretation are carried mostly by frequencies above 1,000Hz. In ordinary conversation the sounds /f/ and /v/ are most difficult to hear and are responsible for 50% of mistakes of interpretation.

Gardner, M. Lateral localization at 0^{o} or near 0^{o} oriented speech signals in anechoic space. J.A.S.A., 1968, 44, 797-801.

Twenty normal hearing listeners localized speech signals in the intersection of the median and horizontal plane. Under the test conditions the average error of lateral or angular localization was 1.5^{o}. In addition, an average listener bias of 1.1^{o} and a group bias of less than $\pm .1^{o}$ were also found when the speech signals were presented over a wide range of levels from a source located among similar units displayed at various angles and distances from S, average shifts as large as 5^{o} were observed.

Gardner, M. B. Distance estimation of 0^{o} or aparrent 0^{o} oriented speech signals in anechoic space. J.A.S.A., 1969, 45, 47-53.

Estimation of distance of recorded and live speech sound demonstrated the following: loudspeaker sources were essentially judged independent of the actual distance involved (3-30 ft). This result held whether single, multiple symmetrical or asymmetrical arrays were used. When the source was a live voice a marked degree of accuracy in estimating relative distance was found depending on the type of vocal output employed and on the degree to which normal level changes with distance were eliminated as a parameter.

Harltey, R. V. L., & Fry, I. C. The binaural location of complex sounds. Bell Systems Tech. J., 1921, 1, 33-42.

The location of complex sounds involves three processes: (1) The resolution of the sound into its component tones, (2) the independent location of each separate component, (3) the formation of a conscious judgment of the position of the source based on the locations of the individual images. The greatly increased amount of data available when the sound is complex has different effects on the final result according to coincidence of the different images. If they coincide, accuracy and sense of certainty are increased. When they do not, confusion arises and the final result is likely to reflect individual differences of the observers.

Hirsh, I. J. The relation between localization and intelligibility. J.A.S.A., 1959, 22, 196-200.

Normal listeners judged intelligibility of speech in the presence of a noise masker. It was found that when the azimuths of the sources of the speech and the noise signals are changed relative to each other the threshold of intelligibility changed by small but consistent amounts. When the sources were close together the threshold was high; when the sources are far apart the threshold was reduced. Although this relation is partially confounded by intensities at the ears the factor of localization appears to play a significant role especially when two ears are used and the head is allowed to move.

Hirsh, I. J. Masking of speech and auditory localization. Audiology, 1971, 10, 110-114.

Report on clinical studies on normal observers shows that both normal and hearing aid user S's better understood speech when it was presented against a background of noise when (a) speech and noise come from spatially separated sources, or (b) the listener could localize the sounds. The listener's ability to localize was greater when (a) he could use two ears or two aids with microphones separated and/or (b) aid or aids were located on a moving head.

It is likely that auditory localization of separate acoustic sources is only one of several means for making a signal more easily discriminable from simultaneous noise or other background.

Hochberg, I. Auditory localization of speech as a function of interaural auditory acuity. J. of Aud. Res., 1963, 3, 141-147.

S's were grouped according to their average interaural acuity into four categories; 0-5db, 6-10db, 11-20db, 21db or greater. Analysis of the data revealed subjects in the latter group demonstrated a concommitant decrement in ability to auditorily localize a speech signal compared to ability of other groups. It is concluded that normal listeners demonstrate some degree of auditory localization difficulty as when their average interaural acuity levels exceed 21db.

Hochberg, I. Median plane localization of speech. J. Aud. Res., 1966, 6, 277-281.

Sixty-five normal hearing adults localized speech in the front and rear median plane. Localization was found to be more accurate in the front quadrant than rear. Front-rear reversals were equally distributed in the two quadrants. S's tended to confuse either front or rear quadrant almost exclusively but not both. S's who did not demonstrate front-rear confusions were more accurate localizers than those who demonstrated reversals.

Tonning, F. M. Directional audiometry. Acta Otolaryngol., 1971, 72, 352-357.

Thirty normal hearing S's were tested on intelligibility of speech in relation to azimuth of the source, both with and without background noise. Directional threshold of intelligibility (DTI) was determined for various azimuths with/without noise. Average DTI's were greater in front and back of the listener than right or left of the observer without noise. With background noise poorest DTIs were found with both loudspeakers in the same position and both positioned coaxially in front and behind. The best DTI occured when the signal speaker was aimed to right/left of observer while the noise speaker was behind.

Miscellaneous Papers and Books in the Area of Sound Localization

Blauert, J. Binaural localization: multiple images and application in room and electroacoustics. In R. W. Gatehouse (Ed.) Localization of Sound: Theory and Applications, Amphora Press, 1982

The problem of how the lateralization mechanism handles interaural arrival time and level differences when forming image position is dealt with through several conditions under which multiple images and diffusely localized images were evaluated. Results and hypotheses developed are as follows (1) arrival time differences produced from sources having dissimilar frequency spectra lead to a splitting or broadening of sound images, (2) the "lateralization power" of arrival time differences in the frequency range up to about 1.6kHz is larger than that in higher frequency regions, (3) to achieve an effect of spaciousness in a concert hall or by means of electroacoustical devices, it is useful to provide distinct variations of the arrival time differences as a function of frequency, especially in the range below 16kHz.

Blauert, J. Binaural localization. Scandinavian Audiol., 1982, Supp. 15, 7-26.

A review is made of issues which are relevant to the formation of spatial positions and extents of auditory events in the case of two normally functioning ears. Physical aspects under consideration are measurement and analysis of the transfer functions of the external ears. These transfer functions are responsible for encoding information about the spatial characteristics of sound fields into the ear input signals. The hearing system can decode this information by evaluating interaural and monaural cues of these signals.

Boder, D. P., & Goldman, I. L. The significance of audible onset as a cue for sound localization. J. Exp. Psychol., 1942, 30, 262-292.

Ninety-five S's with normal hearing were tested for localization of steady versus intermittent sounds. The results clearly indicate better localization to intermittent stimuli. The authors suggest that clear on-off response to the cortex to intermittent or discrete tones represents and important bioelectrical component of the higher integrative processes, such as auditory space perception.

Gardner, M. B. Image fusion, broadening, and displacement in sound localization. J.A.S.A., 1969, 46, 339-349.

A number of conditions under which the fusion of two or more spatially separated complex signals (speech, music) into a single apparent image are presented. If both quality and arrival-time conditions ar fully met, complete fusion occurs and a single source is heard. If the conditions are only partially met only a partial fusion or image broadening occurs. The degree of broadening may be relatively small or may be sufficient to fill the intervening space between the sources. For certain combinations of parameters the creation of a single image either inside or outside these boundaries (image displacement) may occur.

Gatehouse, R. W. (Ed.) Localization of Sound: Theory and Applications. Amphora Press, Groton, CT, 1982.

Papers in the area of sound localization presented at the University of Guelf symposium July 3-6, 1979 are presented. Areas covered are external ear response, models of sound localization, binaural localization, anatomical pathways, primate auditory localization, monaural perception of azimuth, development of auditory localization, acoustic head related transfer functions and underwater localization.

Haggard, M. P., & Hall, J. W. Forms of binaural summation and the implications of individual variability for binaural aids. Scandinavian Audiol., 1982, Supp. 15, 47-63.

The advantages which a two-ear system has over a one-ear system appear to be manifold but not understood in detail. All probably play some role in the generally recognized advantage of binaural aids in offsetting auditory disabilities. Several possible forms of binaural summation are distinguished and their role discussed. Experimental results with normally-hearing S's and with aid users show that binaural summation is likely to lead to gain settings of about 6db lower than otherwise equivalent monaural amplification. In some cases there may be a direct cause benefit. However, individuals differ systematically in the extent to which they show this effect. Evidence is reported of an association between binaural summation and binaural advantage.

Möller, A. R. Signal processing in the auditory system and how it may relate to binaural hearing. Scandinavian Audiol., 1982, Supp. 15, 65-79.

Examples are shown that demonstrate that the nervous system places great emphasis on coding the temporal frequency and amplitude changes in sounds, and important binaural information might be obtained from detection of the interaural phase differences in these frequency and amplitude changes even though the carrier frequencies are too high for direct interaural time comparison. It is therefore, likely that if more complex sounds were utilized as stimuli, neurophysiological experiments on the processing of binaural information would reveal additional mechanisms which could not be predicted from the results obtained with pure tones and clicks.

Morimoto, M., & Ando, Y. On the simulation of sound localization. In R. W. Gatehouse (Ed.) Localization of Sound: Theory and Application. Amphora Press, 1982.

Computer simulation of sound localization through the use of the measured head-related transfer function of ears with different size pinnas was performed. The results of localization tests of simulated sound sources showed the following. In spite of the fact that sound sources were reproduced here through two loudspeakers located in a tranverse plane, natural sound localization in both horizontal and vertical planes can be performed with nearly the same accuracy as real sound sources. The differences between individual head related transfer functions affect the accuracy of simulated localization, particularly in the median plane.

Musicant, A. D., & Butler, R. A. Binaural horizontal plane localization: spectral cues as a factor. J.A.S.A., 1982.

Spectral cues due to pinna effects play a major role in binaural horizontal plane localization. One major effect is discrimination of front from rear. The data suggest that occluding the pinna does not change the shadow effect as much as it reduces and obscures whatever amplification or attenuation effect the pinna might have upon different segments with the high frequency spectrum. Beyond this gross error pinna cues affect accuracy of localization at particular angles also. Most likely the auditory system relies heavily upon spectral cues when high frequencies are available to (1) resolve the cone of confusion, and (2) sharpen resolution about an angle once the determination of front from rear has been made.

Pedersen, O. J., & Poulsen, T. (Eds.) Binaural effects in normal and impaired hearing. Scandinavian Audiolgy, Supp. 15, 1982.

A series of papers delivered at the 10th Danavox Symposium June 8-11, 1982 Klarskovgard, Denmark are presented. Areas of interest are binaural localization, binaural interaction and localization with various hearing impairments, the problem of front-back localization in binaural hearing, and the effectiveness of binaural hearing aids.

Perrott, D. R., Musicant, A., & Schwethelm, B. The expanding-image effect: the concept of tonal volume revisited. J. Aud. Res., 1980, 20, 43-55.

Three experiments are reported. In Experiment I fourteen S's estimates of "width" of tonal images, diotically presented under earphones, showed an increase with lower frequency and longer duration of the source. In Experiment II six S's demonstrated tonal volume depended systematically on both intensity level and duration of the source. Experiment III showed judgments of vertical extent to be more variable than lateral judgments and were difficult to distinguish from those for loudness. It was shown however, that spatial extensity judgments are not identical to those for loudness. The apparent size of an auditory image is dyanamic, that is, it grows as a function of duration. The expanding image effect may account for the difficulty encountered by early research in this area.

Richardson, B. Using the skin for the purpose of sound localization. In R. W. Gatehouse (Ed.) Localization of Sound: Theory and Application. Amphora Press, 1982.

The results of three experiments support the view that tactile "artificial ears" should include information to permit sound localization because (1) the detection of the source of a sound is of obvious immediate benefit and (2) the ability to localize sound is important for unscrambling the competing sounds which so often occur in natural environments. A workable sound sensor has been constructed and empirical tests are in progress to evaluate its value.

Searle, C. L., Braida, L. D., Davis, M. F., & Colburn, H. S. Model for auditory localization. J.A.S.A., 1976, 50, 1164-1175.

A mathematical model based on statistical decision theory is presented that represents the human auditory localization function. The model is applied to most horizontal and vertical localization experiments reported over the previous ten years including over 200 S's and 20,000 trials. Using non-linear regression, estimates of the standard deviations are determined for four of the sources for cues to localization; (1) interaural and monaural head shadow (2) interaural pinna, (3) monaural pinna and (4) shoulder bounce. The model provides relatively good fit to the published localizaton results.

Thurlow, W. R., & Jacques, J. C. Localization of two noise sources overlapping in time. J. Speech and Hear. Res., 1975, 18, 663-671.

Thirty-seven normal hearing subjects were tested for accuracy of localization of two independent wide-band noise sources overlapping in time. S's had little difficulty in localizing when the sources were separated by 55 degrees and located in front or in back of them with one source 10^{o} from the midline. When located to the side of S perception of two sources tended to improve significantly as time between onset of the sources was increased to 10 msec.

Thurlow, W. R., Marten, A. A., & Bhatt, B. J. Localization after effects with pulse-tone and pulse-pulse stimuli. J.A.S.A., 1965, 37, 837-842.

When a pulse is presented from one position in space near in time to the beginning of a tone burst coming from another position in space, the tone burst may be perceived to be displaced toward the pulse. A related type of displacement occurs when two pulses separated in space occur with a small time separation. Another type of effect is one in which a pulse appears to be funneled into the spatial location of another that precedes or follows it by a small time interval. A "place" model is presented to help explain these effects.

Wallach, H., Newman, E. B., & Rosenzweig, R. The precedence effect in sound localization. Amer. J. Psychol., 1949, 62, 315-336.

This study is concerned with the presentation of two nearly identical sounds reaching the ears from different directions when one follows the other with a slight delay. The upper limit of the fusion interval varies from 5 msec delay for single clicks to 40 msec for sounds of complex character. If two brief sounds are heard the location is determined by the first arriving sound (precedence effect). Precedence is best demonstrated by transient sounds.

Weinrich, S. The problem of front-back localization in binaural hearing. Scandinavian Audiol., 1982, Supp. 15, 135-145.

Some investigations concerning the problem of front-back discrimination in normal hearing S's are described. Three experiments are included; some objective measurements of transfer functions of the ears of four S's, horizontal plane simulations, and modifications of artificial-head signals in order to bring about directional inversion in the horizontal plane. It is concluded that S's are able to utilize small individual characteristics in the transfer functions of their own outer ears to distinguish front and back.